



Baymani-Nezhad, M., & Han, D. (2018). ERM model analysis for adaptation to hydrological model errors. *Acta Geophysica*, 66(4), 741–753. <https://doi.org/10.1007/s11600-018-0137-y>

Publisher's PDF, also known as Version of record

License (if available):
CC BY

Link to published version (if available):
[10.1007/s11600-018-0137-y](https://doi.org/10.1007/s11600-018-0137-y)

[Link to publication record in Explore Bristol Research](#)
PDF-document

This is the final published version of the article (version of record). It first appeared online via SPRINGER at <https://link.springer.com/article/10.1007%2Fs11600-018-0137-y>. Please refer to any applicable terms of use of the publisher.

University of Bristol - Explore Bristol Research

General rights

This document is made available in accordance with publisher policies. Please cite only the published version using the reference above. Full terms of use are available:
<http://www.bristol.ac.uk/red/research-policy/pure/user-guides/ebr-terms/>



ERM model analysis for adaptation to hydrological model errors

M. Baymani-Nezhad¹ · D. Han²

Received: 28 October 2017 / Accepted: 30 March 2018

© Institute of Geophysics, Polish Academy of Sciences & Polish Academy of Sciences 2018

Abstract

Hydrological conditions are changed continuously and these phenomenons generate errors on flood forecasting models and will lead to get unrealistic results. Therefore, to overcome these difficulties, a concept called model updating is proposed in hydrological studies. Real-time model updating is one of the challenging processes in hydrological sciences and has not been entirely solved due to lack of knowledge about the future state of the catchment under study. Basically, in terms of flood forecasting process, errors propagated from the rainfall-runoff model are enumerated as the main source of uncertainty in the forecasting model. Hence, to dominate the exciting errors, several methods have been proposed by researchers to update the rainfall-runoff models such as parameter updating, model state updating, and correction on input data. The current study focuses on investigations about the ability of rainfall-runoff model parameters to cope with three types of existing errors, timing, shape and volume as the common errors in hydrological modelling. The new lumped model, the ERM model, has been selected for this study to evaluate its parameters for its use in model updating to cope with the stated errors. Investigation about ten events proves that the ERM model parameters can be updated to cope with the errors without the need to recalibrate the model.

Keywords Real-time model updating · Forecasting errors · Concentration time · Time to peak

Introduction

Land use/land cover change and climate change have significant influences on catchment hydrological characteristics. The appearance of these phenomena has potential effects on generating unusual flood events and may lead to produce various types of flooding. Study about these natural occurrences and their interaction with hydrological models has been mentioned in the literature with explanation of methods to control and reduce their risks (Arnell 1999; Wilby et al. 1994; Xu 1999; Dibike and Coulibaly 2005; Hagg et al. 2007; Charlton et al. 2006).

Irregular rainfall events have direct linkage with anticipated floods around a catchment. Consequently, performing precautionary actions like developing a model for

real-time flood warning can help reduce flood damages during a flood event significantly. Flood forecasting is an important part of water resource management activities related to flood warning, flood control or reservoir operation (Yang and Michel 2000), but still lots of efforts are required to develop highly accurate models for operational hydrology. Real-time flood forecasting is important for every day operation, management of water control systems and for emergency cases where protection of life and property is concerned (Lardet and Obled 1994). In many countries, flood warning systems come towards the top of the government's policy priority list (Penning-Rowsell et al. 2000). Accurate real-time flood forecasting with an adequate lead time can help to confront flood hazards in an efficient time period. Real-time flood forecasting model and an updating technique should be integrated (Yu and Chen 2005) which is applied by operators to predict flood events.

All flood forecasting models are a simplification of the reality and they simulate the flood events with errors depending on the model structures and their adaptability with the changes in hydrological conditions. Hence, applying a number of efficient adaptive strategies may

✉ M. Baymani-Nezhad
matin.baymani@kiau.ac.ir

¹ Department of Civil Engineering, Karaj Branch Islamic Azad University, Karaj, Iran

² Water and Environmental Manager Center, University of Bristol, Bristol, UK

reduce model errors. Studies about flood forecasting models can be divided into two categories: (1) developing new models (Beven 1993; Bartholmes and Todini 2005; Yakowitz 1985), (2) developing efficient methods to reduce specific sources of uncertainties and improving the current models (Brath et al. 2002; Younis et al. 2008). The first category was studied in 2013 by Baymani-Nezhad and Han by developing a new efficient lumped rainfall-runoff model called ERM (Fig. 1). The model performance was evaluated by the real data obtained from three different catchments. The model efficiency in terms of model calibration and validation was proved by numerical and visual inspection (Baymani-Nezhad and Han 2013). The current study discusses about the second category to evaluate the ERM model's adaptive performance in terms of real-time flood forecasting.

The model updating proposed in this study is model parameter updating by finding a linkage between the model parameter and hydrological conditions as an approach to explore model adaptivity by synthetically generated rainfall-runoff data to test the model's capability to adapt to the changes. The reason for using the ERM model is due to its clarity, simplicity with a small number of model parameters.

The ERM model has reliable performance when one routing component is used and a brief difference is observed with two routing components. Hence due to the reduced number of calibrated parameters in terms of model updating, the ERM model with one routing component (eight parameters) has been selected. Two scenarios will be discussed in the following sections: updating the model before the forecasting process and preparing the model based on predicted hydrological changes. For the first part, a continuous event is selected and the ERM parameters are calibrated based on the observed runoff, and then ten single events are investigated to update them. Three parameters of the ERM model compatible with the model errors are selected in the updating process. The model updating is carried out just by changing these parameters and the rest of parameters should be kept on their optimum levels. In this way, if the parameters update the model properly, there is no need to recalibrate the model which is not an easy process especially in real-time flood forecasting.

Existing errors in hydrological modelling

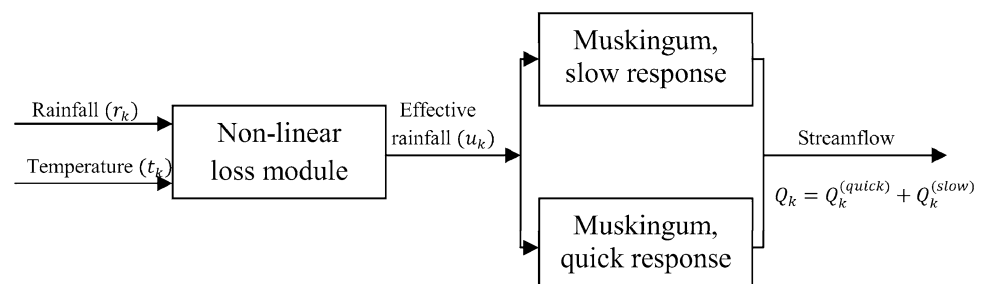
Typically, four types of errors are illustrated during rainfall-runoff modelling (Fig. 2). These four errors are called volume error, shape error, timing error and random error. The altered runoff percentage may cause the volume error which could be due to unexpected changes in the soil moisture content. The altered delay time between the rainfall event and generated runoff on the catchment outlet is due to change in rainfall location which causes the timing error in the model, and finally the shape error occurs due to change on the catchment concentration time. Even without the existence of volume, shape or timing errors, the model may still produce inaccurate forecasts, since a real catchment is very complex and it is impossible to create a mathematical model (with only a limited number of parameters) that could perfectly replicate the catchment response over all modes of behaviour. This problem is caused due to random errors which are unpredictable and commonly, the models are not capable of predicting and solving them.

Obviously, predicting the hydrological changes and preparing the model parameters based on the new conditions can make the forecasted results more reliable in comparison with modelling by the optimum parameters which are obtained under the calibration conditions. The optimum parameters have been estimated based on a series of recorded data for a certain period of time. However, diversity of hydrological condition at any time make this problem more evident and the model should be adapted based on the new conditions to achieve more reliable flood forecasts.

Catchment conditions for volume error

The source of volume error could be linked with changes in soil moisture content which causes changes in runoff volume in the catchment outlet. These changes may be due to variations in land use/land cover, soil compaction, etc. (Chiew et al. 1995; Fu et al. 2003). Nguyen et al. (1998) did an investigation about the impact of animal grazing on soil physical properties and they confirmed that grazing animals like cattle could change the soil properties and reduce water infiltration into the soil. The changing scale of the soil characteristics may be influenced by the type of

Fig. 1 Generic structure of the ERM model components



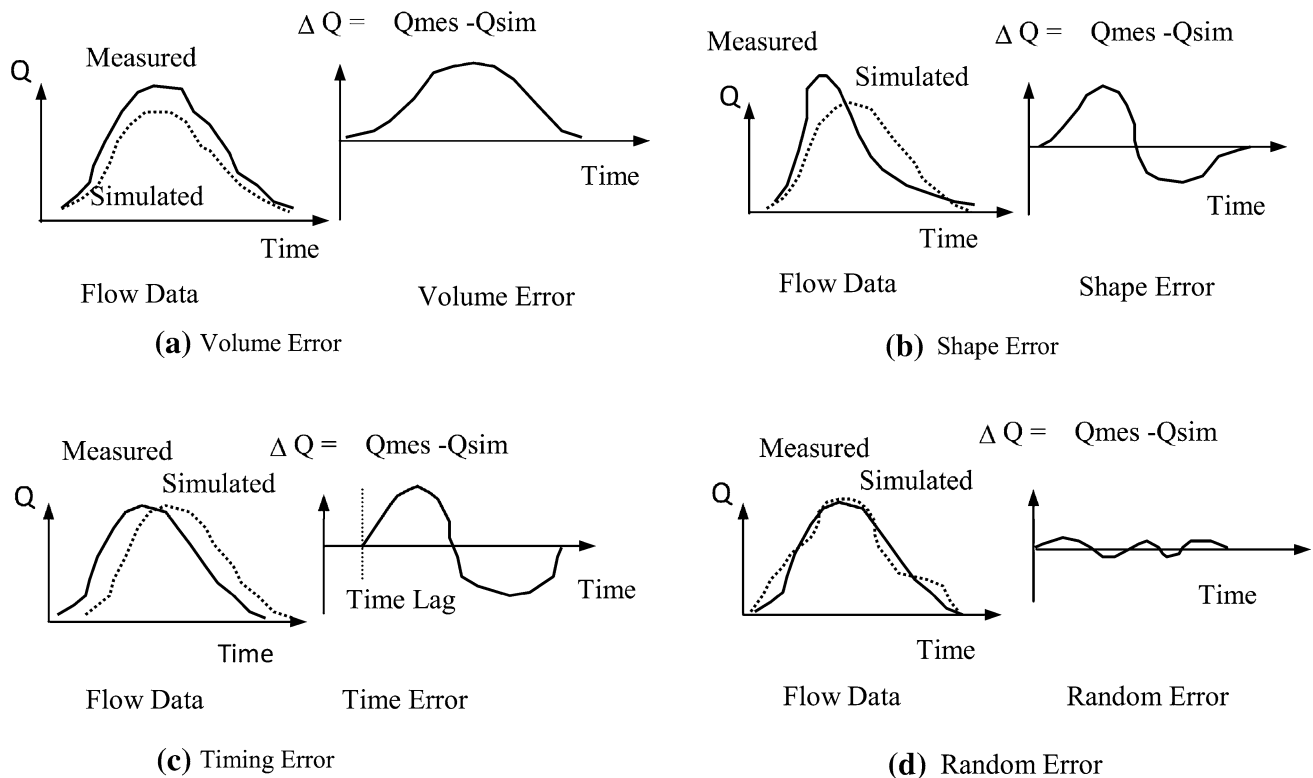


Fig. 2 Flow forecasting errors (Han 2011)

animals, pasture cover, stocking rate, grazing duration, soil texture, soil structure and soil organic matter content (McCalla et al. 1984). In addition to the animal grazing, a number of farm activities such as farm machines operation and land tillage are important factors to change the soil density which could alter rainfall infiltration into the soil.

Catchment conditions for timing error

It takes time for the rainfall to reach the river outlet. For a lumped hydrological model such as the ERM model, the timing error would occur if the delay time between rainfall and runoff response from a catchment changes. With different rainfall locations in the catchment (e.g., upper reach, middle reach or lower reach), water arrives at the catchment outlet at different times. If the rainfall is near the catchment outlet, the flow will arrive at the outlet sooner than rainfall far away from the outlet. Hence, selecting a reliable delay time between effective rainfall and the time for starting runoff generation could be helpful to determine the timing errors.

Catchment conditions for shape errors

The shape error is generally linked with catchment concentration time. Many factors can influence the concentration time. For example, different intensities of rainfall may produce different concentration times (raindrops reach

the river outlet faster under heavy rainfall intensity than lighter rainfall intensity). Other factors which influence the shape of hydrograph are flow paths with different roughness, slope and length. At the moment, most of lumped rainfall-runoff models assume a fixed catchment concentration time and are unable to overcome the shape error. Hence, assuming a unique concentration time for all storm events around a catchment may cause uncertainties in terms of modelling process. But, by recognising the concentration time (or time to peak) estimated for an event and updating specific parameters of the model, it is possible to update the model according to the new conditions. To overcome difficulties caused by the shape error and update the model to reach a more accurate forecast, the shape of the observed hydrograph is rotated under a certain degree, and then the model parameters are updated based on the new observed hydrograph. The link between the required angle for rotating the hydrograph and the predicted time to peak will be described in the followings sections.

Altered hydrographs to reflect the catchment conditions

The mechanism of model updating in this section is categorised into two classifications: first reducing the modelling errors in simulated runoff hydrograph (before

forecasting) and second predicting the possible changes in hydrological conditions and adjusting the model parameters according to the new conditions. For this reason, the observed hydrograph is changed according to the predicted changes and the simulated hydrograph and the model parameters are updated to simulate a runoff hydrograph similar to the altered hydrograph. To cope with each type of error, just one of the ERM parameters is updated. Therefore, instead of recalibrating all of the model parameters, the most effective parameters related to the model errors will be updated. In some cases, the modelling errors could be a mix of all the errors, hence it might be required to update all the three parameters at the same time to cope with all the sources of errors. Consequently, any changes on the system could be carried out by just playing with maximum three parameters. The change of the observed hydrograph to reflect the hydrological changes and selecting the proper parameters of the ERM model will be described in the following sections.

Simulate the volume error conditions

By predicting the sudden changes in soil moisture content and estimating the current soil moisture content, the observed hydrograph will be changed based on the difference between two conditions. Therefore, all points in the observed hydrograph will be increased (or decrease) up to a percentage of the difference between the two conditions. Figure 3 shows a schematic plot of increasing the observed runoff hydrograph to simulate the volume error.

Simulate the timing error conditions

Timing error condition is explored by shifting the observed runoff hydrograph by a specified duration (e.g., 3 h). In this term, the difference between the catchment response times must be estimated and applied to the observed runoff hydrograph. After this process, the simulated hydrograph will be updated based on the new conditions. Figure 4 shows the shifted runoff hydrograph. In a similar way, the most effective parameter is selected to update the ERM model.

Simulate the shape error conditions

As discussed before, the shape error is caused by changes in catchment concentration time. After estimating the concentration time (or time to peak) for the forecasted storm event, the observed hydrograph is rotated based on the new time to peak. Hence, a linkage between the estimated time to peak and required angle for rotation should be addressed. Figure 5 shows the altered hydrograph after rotation.

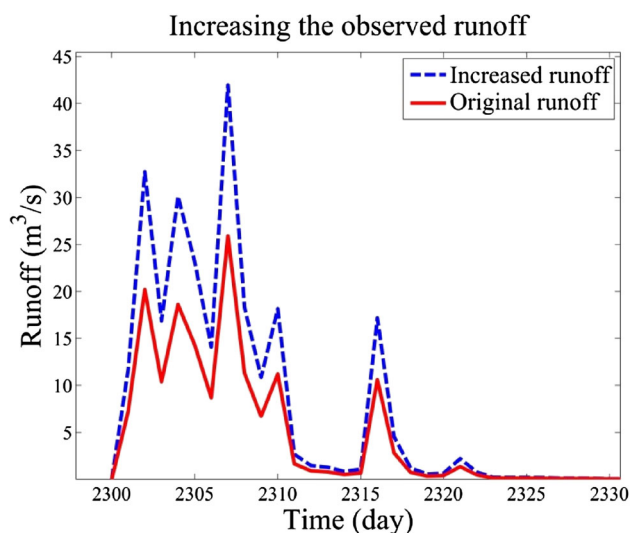


Fig. 3 Increasing the observed runoff for volume error condition

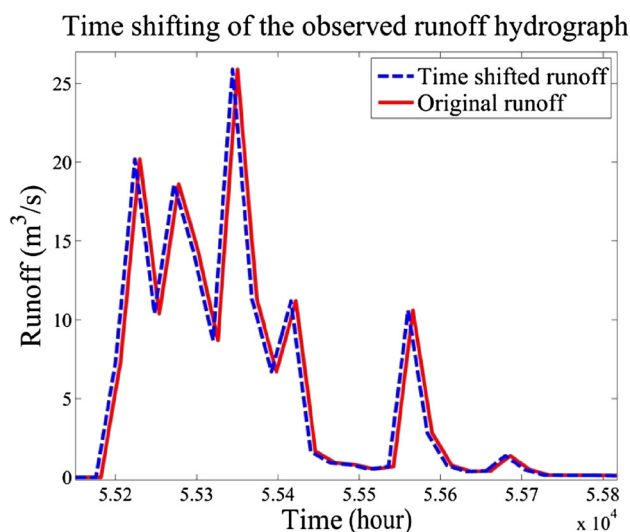


Fig. 4 Shifting the observed runoff hydrograph to simulate the timing error

According to Fig. 5, the time to peak has been changed after the rotation process. The relationship between the new time to peak and the rotation angle can be introduced. In the current study, a method has been proposed to adjust the model under the new condition.

During the current study, the rotation matrix is applied to rotate points on the runoff hydrograph. The rotation matrix under θ degrees is described by the following equations:

$$R_{(\theta)} = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \quad (1)$$

Point (x, y) can be rotated around the point $(0, 0)$ with θ degrees by multiplying the rotation matrix and the final rotation matrix is described by the following rotations:

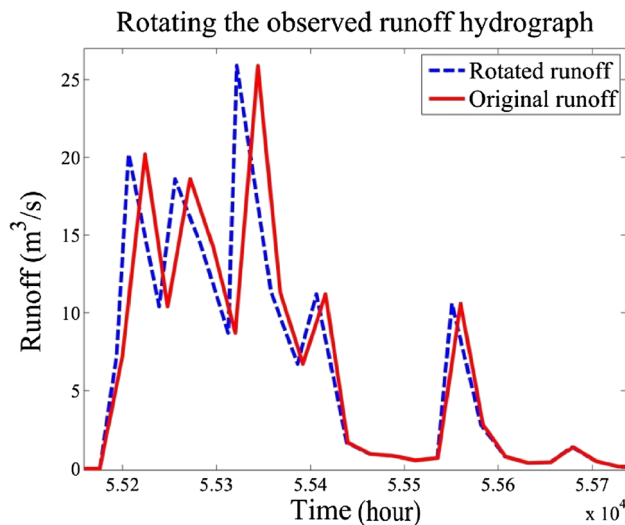


Fig. 5 Rotating the observed runoff hydrograph to simulate shape error condition

$$x_{\theta} = x \cos \theta - y \sin \theta \rightarrow \text{around}(0, 0) \quad (2)$$

$$x_{\theta} = x_0 + (x - x_0) \cos \theta - (y - y_0) \sin \theta \rightarrow \text{around}(x_0, y_0)$$

$$y_{\theta} = x \sin \theta + y \cos \theta \rightarrow \text{around}(0, 0)$$

$$y_{\theta} = y_0 + (x - x_0) \sin \theta - (y - y_0) \cos \theta \rightarrow \text{around}(x_0, y_0)$$

The runoff hydrograph is plotted using runoff records (the y-axis) versus the time (the x-axis). During the hydrograph rotation, each point of the graph is rotated around its mirror on the x-axis. Therefore, using the rotation matrix, a relationship between the degree of rotation and change in the time of concentration is obtained. The following equations are derived for this relationship using the points shown in Fig. 5.

$$t_{\theta} = t_0 + (t - t_0) \cos \theta - (Q - Q_0) \sin \theta \quad (3)$$

$$\begin{aligned} t_{\theta} - t_0 &= -Q \cdot \sin \theta \rightarrow t_{\theta} - t_0 = \frac{\theta}{180} \cdot \pi \cdot Q \rightarrow \theta \\ &= \frac{180 \cdot (t_{\theta} - t_0)}{\pi \cdot Q} \end{aligned}$$

where θ is the rotation degree, t_{θ} is the time to peak after rotation, t_0 is the time to peak before rotation and Q is the runoff records before rotation.

Basically, the area under the runoff hydrograph represents the runoff volume. The aim of the hydrograph rotation is to check the hydrological model adaptivity to the updated runoff hydrograph according to the change of concentration time. In this process, the runoff volume should be maintained (before and after the rotation). After rotating the hydrograph, it was observed that the runoff volume is changed. Hence, to cope with this problem, a coefficient was determined by the following equation:

$$\emptyset = \frac{A_{\text{before}}}{A_{\text{after}}} = \frac{\int_{t_1}^{t_2} Q_{\text{before}} d_t}{\int_{t_1}^{t_2} Q_{\text{after}} d_t} \quad (4)$$

where, \emptyset is the rotation coefficient, A_{before} is the area under the runoff hydrograph (runoff volume) before rotation, A_{after} is the area under the runoff hydrograph after rotation. After rotating the runoff hydrograph by multiplying all of the runoff values by the \emptyset coefficient, the runoff volume is returned to the condition before rotation (Fig. 6). Therefore, the runoff volume is kept constant during the rotation process.

The final rotation equation (Eq. (3)) is proposed to derive the required rotation angle, and the time to peak should be estimated before the rotation and after the rotation. In other words, the rotation angle is estimated by the difference between the predicted time to peak and the estimated time to peak before forecasting. Different types of empirical equations have been proposed to estimate the time of concentration and time to peak such as Kirpich (1940), Johnstone and Cross (1949), Haktanir and Sezen (1990) and Fang et al. (2008).

As a well-known equation in hydrological sciences, the Kinematic wave model was proposed by Morgali and Linsley (1965) to estimate the time of concentration. The equation has been used widely in studies such as McCuen and Spiess (1995), Wong and Chen (1997), etc.

Another empirical equation developed to estimate the catchment concentration time is the Izzard equation (Izzard and Hicks 1946). The study was based on runoff produced by rainfall on a man-made surface such as highway pavement or airfield runway. The Soil Conservation Service (SCS) sheet flow equation was revised based on a modified kinematic wave equation for sheet flow USDA SCS (1986). All the stated equations may be used in the catchments which lack

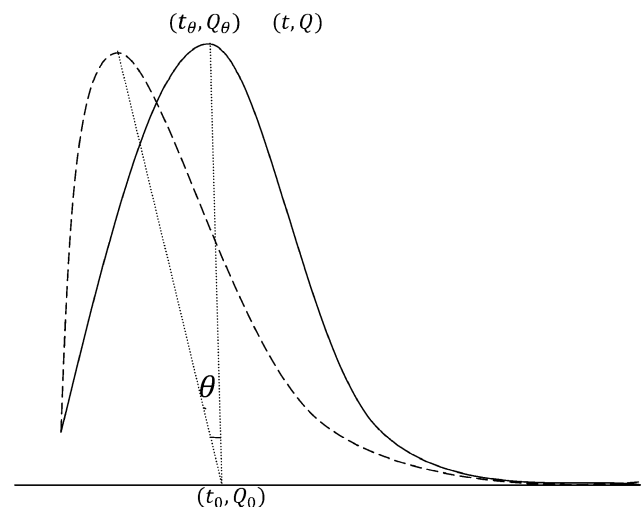


Fig. 6 The components of the runoff hydrograph after and before the rotation

the measured rainfall and runoff data to derive such a relation. Basically, those equations are based on a number of experimental results obtained from specific catchments and under various conditions. Hence, they may have large uncertainties when they are applied to different catchments. As the time to peak is a requirement for the current study, deriving an equation for estimating the time to peak directly by the data obtained from the actual catchment could prevent large errors in the estimation. Hence, in the next section, a particular equation will be derived for the catchment under study.

Developing an empirical equation to estimate time to peak

Time to peak proposed in this study is the time between the beginning of excess rainfall and the time to peak of the hydrograph. To derive an equation to link the time to peak and data obtained from a real catchment, the Brue catchment is selected for the proof of the concept. Based on the experimental equations developed so far, various factors such as land roughness and catchment slope and climate conditions (e.g., rainfall intensity) are effective on the time of concentration and consequently time to peak. In this study, according to data availability, we are looking to develop an equation to estimate time to peak using the center of the storm and the greatest effective rainfall recorded during a storm event. For this purpose, an event-based analysis is carried out by selecting a number of storm events recorded in the Brue catchment. The process is classified into three stages:

- Estimate the center of storm using tipping bucket gauge records around the catchment;
- Derive the time to peak for each storm using effective rainfall and observed runoff hydrograph;
- Fit a surface to extract an equation between the time to peak, the maximum effective rainfall and the center of storm.

To start the process, sixty events have been selected from the Brue catchment in derivation of the equation. The events have been selected from different years to cover varieties occurred around the catchment. The ERM model is used to calculate the effective rainfall assigned to each storm event.

Estimating center of storm

As discussed before, the distance between the center of storm and catchment outlet is required to derive the time to peak equation. The following equation is proposed in the current study to estimate the center of storm:

$$L_s = \sum_{i=1}^n A_i P_i L_i / A \bar{P} \quad (5)$$

where L_s is the distance from the center of the storm to the catchment outlet, A_i is the sub-catchment area, P_i rainfall intensity assigned to the sub-catchment, L_i is the length between the sub-catchment centroid to the catchment outlet, A the total area of the catchment, and \bar{P} is the average rainfall of the catchment

For all of the selected events, L_s should be estimated by the stated equation. The sub-catchment area in the equation is selected as the area covered by each rain gauge. The HYREX study used 49 tipping bucket rain gauges around the Brue catchment to collect rainfall data. Based on the recorded data by the rain gauges, the numbers of gauges in service are different from time to time.

To estimate the average areal rainfall and the area covered by each gauge, the Thiessen polygon method is applied. In this term, the catchment area is divided to a series of polygons and each polygon becomes as a sub-catchment to estimate L_s . After dividing the catchment area into the polygons, rainfall intensity is estimated for each polygon using the gauges records. Also, the centroids of the polygons are estimated to find the distance of the centroid to the catchment outlet. At the end, L_s is calculated for the specific rainfall event.

Application of ArcMap to estimate the center of storm

ArcMap is the main application of Esri's ArcGIS package. This application is widely used in the geospatial sciences to estimate the geological parameters and map processing. In the current study, the ArcMap has been used to create the Thiessen polygons, centroid of polygons and distance between the estimated centroid and catchment outlet. The Brue catchment map is imported into the model to specify the catchment boundary. The gauges are identified by their coordinates and the Thiessen polygons are generated by the feature considered in the ArcMap. Figure 7 shows the spatial distribution of six storms selected in the study. It can be seen that the numbers of sub-catchments are different due to change in the numbers of gauges in service.

According to the definition, time to peak should be estimated by the effective rainfall estimated by the ERM model and the observed runoff assigned to each event. Runoff records were measured hourly in the Lovington gauging station in the HYREX project for the Brue catchment. Hence, the time between the beginning of effective rainfall and the peak of runoff in the observed runoff hydrograph becomes the time to peak associated with the storm. In addition to the time to peak and center

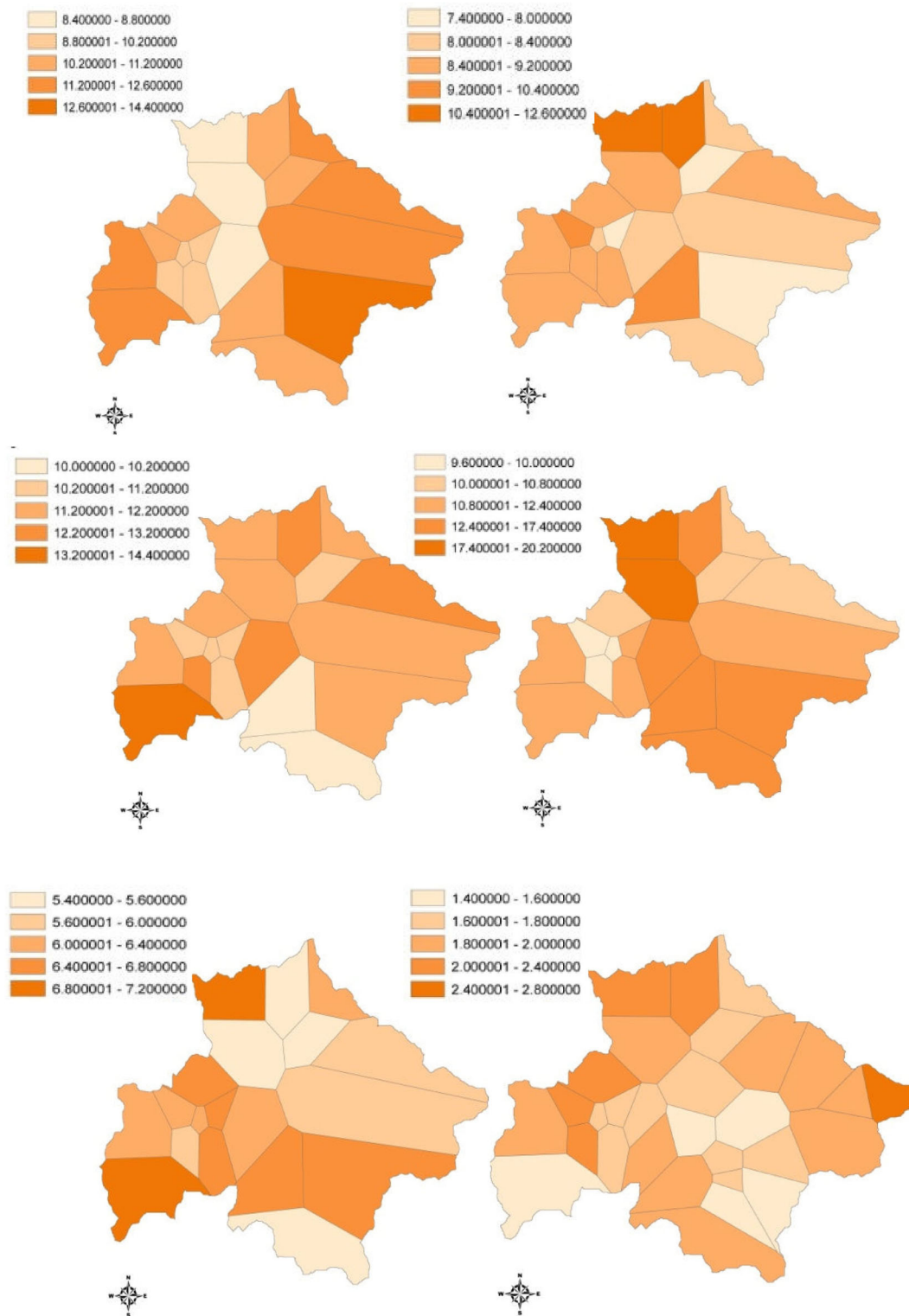


Fig. 7 Spatial distribution of rainfall over the Brue catchment for six storm events

of storm, the maximum effective rainfall over the storm is selected to use in the equation development. To develop the time to peak equation using two variables, the application of surface fitting is highlighted. The surface is

generated in three dimensions (3D) as seen in Fig. 8. The equation assigned to the generated surface is considered as the relationship between the effective rainfall and center of storm with the time to peak. Therefore, by

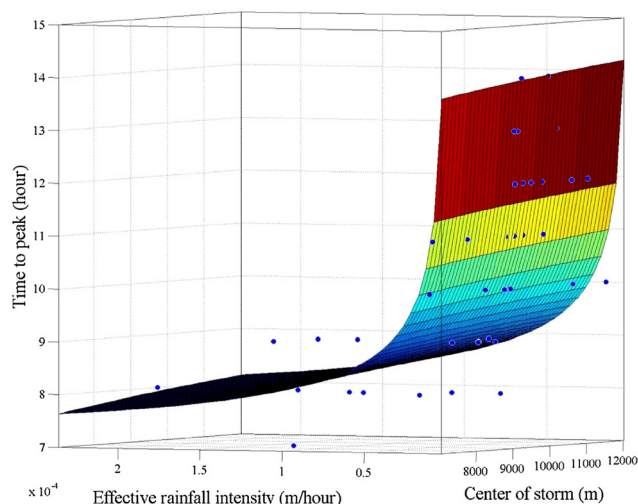


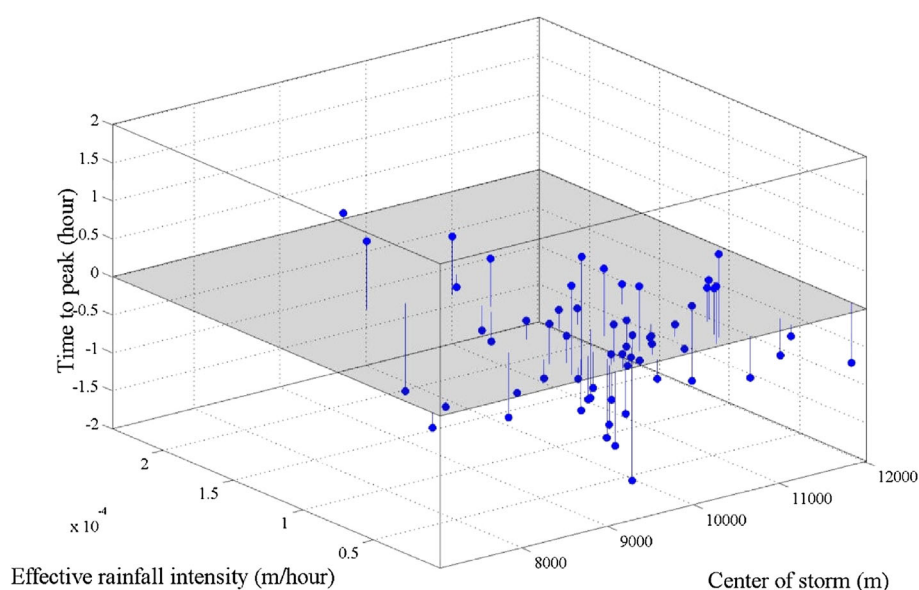
Fig. 8 Fitted surface based on time to peak, center of storm and maximum effective

estimating two variables, the time to peak could be estimated based on the fitted equation. The advantage of using the surface fitting is to achieve more accurate estimation of the time to peak using the data assigned to a certain catchment instead of using the aforementioned experimental equations.

Figure 9 shows a residual plot to assess the quality of the regression which illustrates how much the selected points are with the fitted surface. The surface fitting has been carried out by the MATLAB surface fitting toolbox. The surface equation (Eq. 6) shows a relationship between the three elements under study.

$$t_p = 1.922L_s^{0.136} + 0.036/E_r^{0.417} \quad (6)$$

Fig. 9 Residual plot obtained in terms of surface fitting



where, t_p is time to peak (h), L_s is from the center of storm to catchment outlet (m) and E_r is effective rainfall rate (m/h). As a common representation, the unit of rainfall rate is shown in mm/h, but due to the requirement to the same unit with L_s , mm is replaced by m.

Based on a visual inspection, the fitted surface shown on Fig. 8 could be considered as a reliable fitting for the selected points. Numerical assessment is further required to check the accuracy of the fitted surface by performance coefficients. Three performance coefficients R^2 , RMSE and SSE are estimated by the toolbox automatically. Table 1 shows the coefficients obtained after the fitting process.

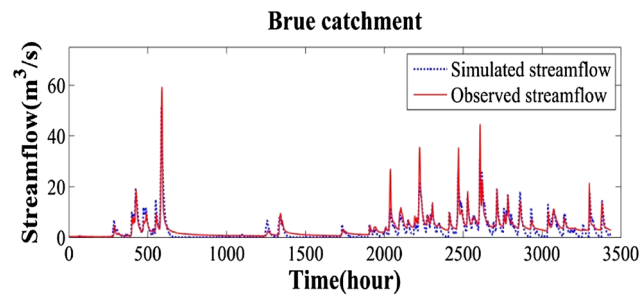
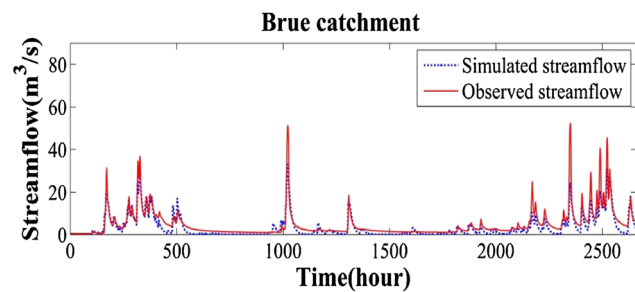
As an individual evaluation, the R^2 value proves the reliability of the fitted surface. The obtained equation can be considered as the unique equation derived using the Brue catchment data and is useful for estimating the time to peak just for the Brue catchment. However, the proposed method could be used in extracting similar equations in different catchments instead of using empirical equations. In following section, the adaptivity of the ERM model will be discussed and tested by a series of real storm events.

Evaluation of the adaptivity of the ERM

The previous sections described the potential errors in rainfall-runoff models and the simulated hydrograph linked to the hydrological changes for model updating. The simulated hydrograph is used to test the adaptivity of the ERM model by adjusting the model parameters. This process will make the model adapt to the new hydrological conditions

Table 1 Performance coefficient estimated after surface fitting

Performance coefficient	Value
SSE(h ²)	23.45
RMSE(h)	0.647
R^2	0.85

**Fig. 10** The simulated runoff by the ERM model using the calibration data**Fig. 11** The simulated runoff by the ERM model using the validation data

and the updated parameters become more reliable to use in flood forecasting.

The model comes with eight parameters which are derived during the model calibration. Also, a parameter called delay time is defined which is the time between the beginning of effective rainfall generation and the starting of runoff generation. This parameter is estimated manually based on trial and error. Among the model parameters, three parameters are selected to cope with volume, shape and timing errors, according to their mechanism and roles in model structure.

To start the evaluation process, two data sets (Figs. 10 and 11) are selected from the Brue catchment database from 1:00, 19th of September 1993 to 05:00, 9th of February 1994 to calibrate the model parameters and from 09:00, 12th of September 1999 to 00:00, 1th of January 2000 for model validation. The simulated and observed runoff hydrographs are plotted on the same figure and their

Table 2 R^2 and RMSE values calculated by the ERM model for the Brue catchment

	R^2	RMSE
Calibration	0.80	2.2 (m ³ s ⁻¹)
Validation	0.78	3.2 (m ³ s ⁻¹)

Table 3 Calibrated parameters of the ERM obtained for the Brue catchments

Parameter	Description	Units	Est. parameters
C	Mass balance	mm ⁻¹	0.000915
τ_w	Reference drying rate	h	300.02
F	Temperature modulation	1/°C	4.28
T_r	Reference temperature	°C	1.8
L	Soil moisture index threshold	–	0.01
P	Power on soil moisture	–	1.16
K	Storage constant	h	20.00
X	Weighting factor	–	0.31

similarities are compared by R^2 and RMSE coefficients (Table 2). The calibrated parameters are listed in Table 3.

To test the ability of the model parameters, event-based analysis is performed by selecting a number of events from the calibrated continuous hydrograph. Real-time flood forecasting is a short-term forecasting and updating the model based on an event before the forecasting process will make the forecasting results more trustable. Therefore, the updating process is carried out on individual events. Ten events are extracted for the process of parameter updating.

In the second stage and before the updating process, for each type of error, a parameter of the ERM model is selected. According to the structure of the ERM model, parameter C (mass balance) is calibrated to ensure that the volume of effective rainfall is equal to the total volume of the observed runoff. Hence, any change in the volume of the observed runoff (as shown in Fig. 3) can be adjusted by regulating the parameter C . Therefore, to overcome the difference between the simulated and observed runoff hydrographs, updating the parameter C could be helpful to cope with this error.

The Muskingum routing scheme embedded in the ERM structure is based on the continuity equation. Therefore, the effective rainfall is assumed as the inflow into the routing system to generate the outflow. According to the difference between the effective rainfall generation and runoff generation over a catchment, a delay time is defined. The timing error is caused by change in delay time depending on the distance of rainfall event to catchment outlet. Hence,

by changing the delay time between the inflow to the catchment (effective rainfall) and catchment response (simulated runoff) in the catchment outlet, the difficulties caused by the timing error (as shown in Fig. 4) could be solved.

The shape error causes the most troubles in the updating process. The parameter K is selected due to its mechanism in the Muskingum routing model. In the experimental studies, the parameter K is defined as the travel time through a reach of the river, hence the parameter is linked with the catchment concentration time and time to peak. After the relevant parameters selected in the updating process, the simulated runoff hydrograph for the case events are updated by changing these parameters. Figures 12, 13, 14, 15, 16, 17, 18, 19, 20 and 21 show the observed, simulated and updated hydrograph for each event.

According to the plotted hydrographs, in some cases, one error type is highlighted. For example Fig. 13 shows a significant timing error between the observed and simulated hydrograph and also some error in runoff volume. To overcome the modelling errors, updating delay time and parameter C could make the simulated hydrograph closer to the observed hydrograph. In another evaluation (Fig. 18), a huge difference in runoff volume is solved by

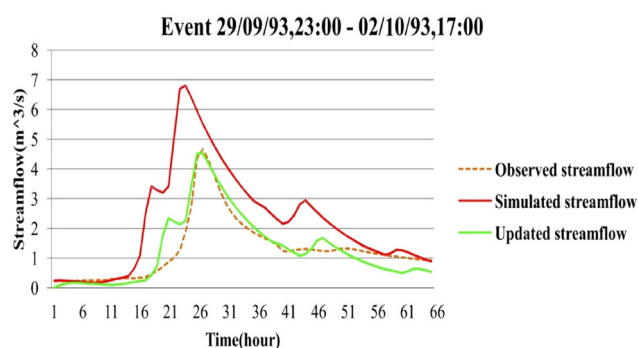


Fig. 12 The single event updating from 29/09/93, 23:00 to 02/10/93, 17:00

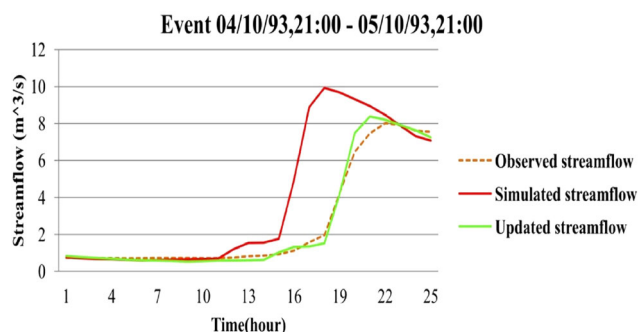


Fig. 13 The single event updating from 29/09/93, 23:00 to 02/10/93, 17:00

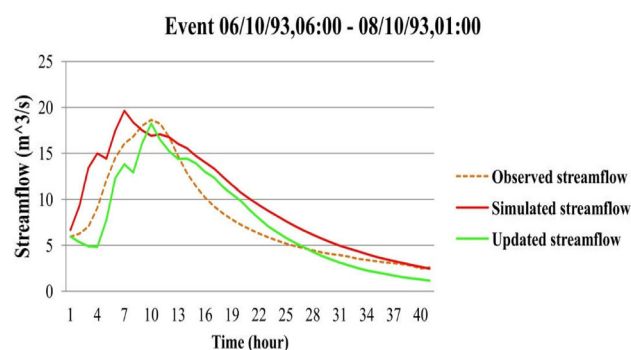


Fig. 14 The single event updating from 06/10/93, 06:00 to 08/10/93, 01:00

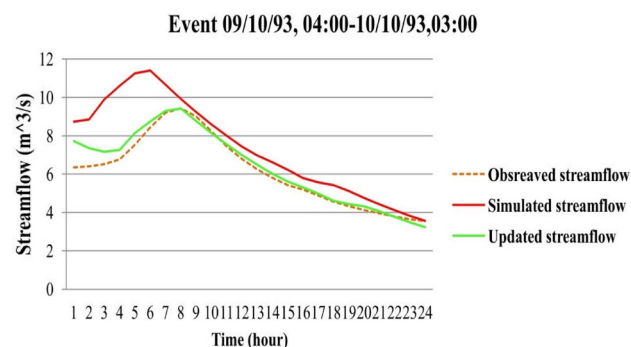


Fig. 15 The single event updating from 09/10/93, 04:00 to 10/10/93, 03:00

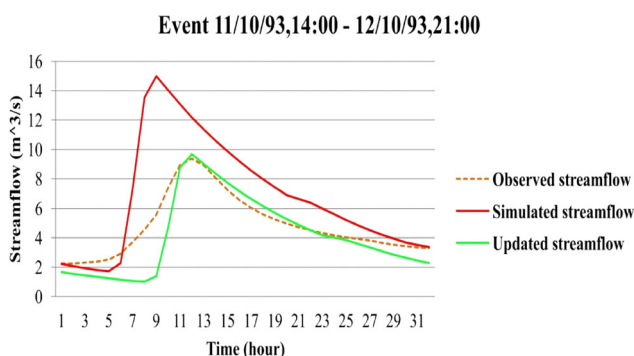


Fig. 16 The single event updating from 11/10/93, 14:00 to 12/10/93, 21:00

changing parameter C . In some hydrographs, three types of errors are observed. In those cases, all of the relevant parameters are updated at the same time to cope with all the error types (Fig. 17). Table 4 shows the updated parameters for the selected events. Also, the R^2 and RMSE coefficients are listed in Table 5. The updated parameters and performance coefficients confirm how much the model parameters are capable of improving the simulated hydrograph without changing the rest of the model parameters.

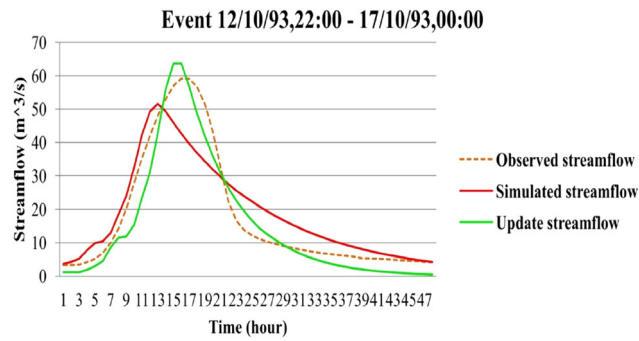


Fig. 17 The single event updating from 12/10/93, 22:00 to 17/10/93, 00:00

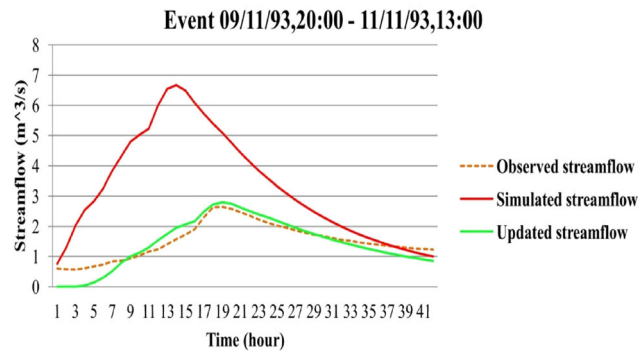


Fig. 18 The single event updating from 14/12/93, 23:00 to 16/12/93, 13:00

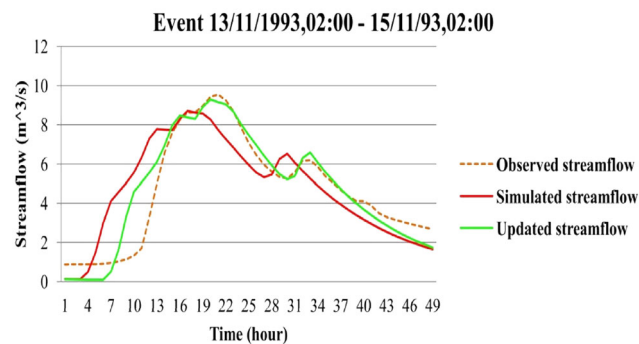


Fig. 19 The single event updating from 13/11/93, 02:00 to 15/11/93, 02:00

A comparison between the hydrographs and the performance coefficients proves that by just updating three model parameters, significant improvements could be achieved. This is important in real-time flood forecasting, because it is easier to adjust 1–3 parameters instead of all 9 model parameters. This process helps to classify the flood events by providing a lookup table based on the flood characteristics. In this method, the best parameters are estimated for each flood event and a number of events are analysed to provide a lookup table which is based on a

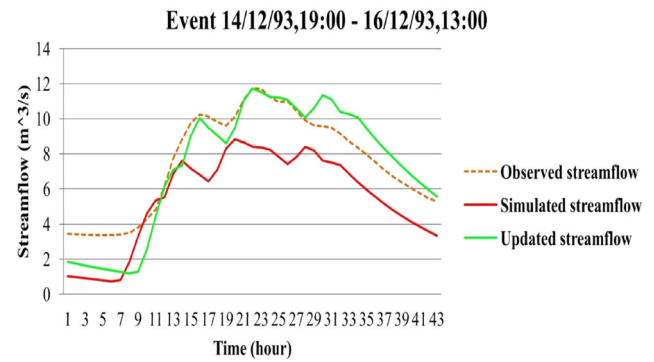


Fig. 20 The single event updating from 14/12/93, 23:00 to 16/12/93, 13:00

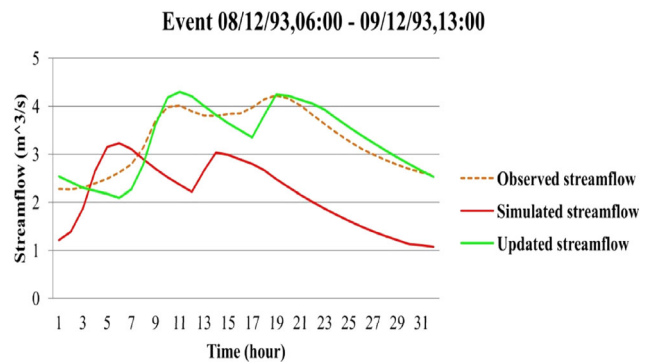


Fig. 21 The single event updating from 08/12/93, 06:00 to 09/12/93, 13:00

Table 4 Updated parameters for the selected events

Event ID	C	K	Delay time (h)
1	0.00037378	16.2	6
2	0.00078587	21.3	6
3	0.00098287	13.4	6
4	0.00079987	19.1	5
5	0.000635587	17.5	6
6	0.00130187	9.5	6
7	0.00040587	26.2	8
8	0.00101587	17.4	6
9	0.000986587	29.4	8
10	0.0011321	21.8	5

catchment condition. In terms of real-time flood forecasting, after recognising the flood characteristics and weather condition, the best parameter set could be selected from the lookup table for forecasting the shape of the hydrograph. Forecasting the flood hydrograph helps to provide an overview about the events ahead and provides interesting information for hydrologists.

Table 5 R^2 and RMSE values calculated by ERM model for the selected single events

Event	Start date	End date	$R^2(\text{sim})$	RMSE(sim)(m^3s^{-1})	$R^2(\text{upd})$	RMSE (upd)(m^3s^{-1})
1	29/09/93—23:00	02/10/93—17:00	– 1.190	1.509	0.854	0.389
2	04/10/93—21:00	05/10/93—21:00	0.144	2.636	0.987	0.320
3	06/10/93—06:00	08/10/93—01:00	0.736	2.580	0.853	1.924
4	09/10/93—04:00	10/10/93—03:00	0.134	1.689	0.944	0.427
5	11/10/93—14:00	12/10/93—21:00	– 1.395	3.135	0.563	1.337
6	12/10/93—22:00	17/10/93—00:00	0.828	7.515	0.926	4.917
7	09/11/93—20:00	11/11/93—13:00	– 16.224	2.434	0.763	0.285
8	13/11/93—02:00	15/11/93—02:00	0.605	1.698	0.878	0.941
9	08/12/93—06:00	09/12/93—13:00	– 3.276	1.344	0.825	0.271
10	14/12/93—19:00	16/12/93—13:00	0.359	2.248	0.800	1.255

Conclusion

The current paper discusses the prevalent errors on runoff simulation. Occurrence of errors during a simulation process is a considerable concern and hence, the model should be monitored continuously to identify the sources of errors and make efforts to update the model. The problem is highlighted in real-time flood forecasting due to limited time to do the process of model updating. Parameter updating is one of the existing methods to adjust the model before starting the forecasting process. In this study, the ability of the ERM model is investigated to cope with volume, timing and shape errors. In the first part of the study, the probable hydrological changes for the model are illustrated by altering the observed hydrograph. Therefore, by changing the observed hydrograph, the model parameters should be updated to cope with the newly altered hydrographs. Due to the importance of time in process of real-time forecasting and updating, for each error type, one of the ERM model parameter is assigned to cope with a certain error type. By selecting the parameters, their abilities are evaluated on real events. Ten runoff events are selected from a continuous runoff simulation to use in updating process. The selected events are not simulated properly in the progress of continuous simulation. In some cases, the existing one error type (e.g., timing error) is observed and in some cases the existence of all the error types are identified, hence updating all the selected parameters to cope with the errors are required. After implementing the parameter updating on the selected event and calculating the performance coefficients, it is confirmed that the ERM parameters have reliable flexibility to cope with the three possible errors in the simulated hydrographs, without a need to recalibrate the model parameters.

Consequently, the ERM model parameters are updated in two ways: (1) updating the model parameters before

starting the forecasting process to reduce difference between the simulated and observed runoff hydrographs; (2) predicting the hydrological changes and alerting the observed hydrograph accordingly, and updating the model parameters based on the new observed hydrograph. Obviously, using the updated parameters is more suitable in new conditions, in comparison with the optimum parameter set. As for the future work, developing a comprehensive model to predict the hydrological changes could be mentioned as a supplementary action to apply in terms of parameter updating. In this way, the amounts of changes are predicted and will be applied to the observed hydrograph and the model will be prepared under new conditions.

References

- Arnell NW (1999) The effect of climate change on hydrological regimes in Europe: a continental perspective. *Glob Environ Change* 9(1):5–23
- Bartholmes J, Todini E (2005) Coupling meteorological and hydrological models for flood forecasting. *Hydrol Earth Syst Sci Discuss* 9(4):333–346
- Baymani-Nezhad M, Han D (2013) Hydrological modeling using effective rainfall routed by the Muskingum method (ERM). *J Hydroinform* 15(4):1437–1455
- Beven K (1993) Prophecy, reality and uncertainty in distributed hydrological modeling. *Adv Water Resour* 16:41–51
- Brath A, Montanari A, Toth E (2002) Neural networks and nonparametric methods for improving real-time flood forecasting through conceptual hydrological models. *Hydrol Earth Syst Sci Discuss* 6(4):627–639
- Charlton R, Fealy R, Moore S, Sweeney J, Murphy C (2006) Assessing the impact of climate change on water supply and flood hazard in Ireland using statistical downscaling and hydrological modelling techniques. *Clim Change* 74(4):475–491
- Chiew F, Whetton P, McMahon T, Pittock A (1995) Simulation of the impacts of climate change on runoff and soil moisture in Australian catchments. *J Hydrol* 167(1):121–147
- Dibike YB, Coulibaly P (2005) Hydrologic impact of climate change in the Saguenay watershed: comparison of downscaling methods and hydrologic models. *J Hydrol* 307(1):145–163

- Fang X, Thompson DB, Cleveland TG, Pradhan P, Malla R (2008) Time of concentration estimated using watershed parameters determined by automated and manual methods. *J Irrig Drain Eng* 134(2):202–211
- Fu B, Wang J, Chen L, Qiu Y (2003) The effects of land use on soil moisture variation in the Danangou catchment of the Loess Plateau, China. *Catena* 54(1):197–213
- Hagg W, Braun L, Kuhn M, Nesgaard T (2007) Modelling of hydrological response to climate change in glacierized Central Asian catchments. *J Hydrol* 332(1):40–53
- Haktanir T, Sezen N (1990) Suitability of two-parameter gamma and three-parameter beta distributions as synthetic unit hydrographs in Anatolia. *Hydrol Sci J* 35(2):167–184
- Han D (2011) Flood risk assessment and management. Bentham Science Publishers
- Izzard CF, Hicks W (1946) Hydraulics of runoff from developed surfaces. *Highway Res Board Proc* 26:129–150
- Johnstone D, Cross WP (1949) Elements of applied hydrology. Ronald Press Company, New York
- Kirpich Z (1940) Time of concentration of small agricultural watersheds. *Civ Eng* 10(6):362
- Lardet P, Obled C (1994) Real-time flood forecasting using a stochastic rainfall generator. *J Hydrol* 162(3):391–408
- McCalla GR, Blackburn WH, Merrill LB (1984) “Effects of live stock grazing on infiltration rates”. Edwards Plateau of Texas. *J Range Manag* 37:265–269
- McCuen RH, Spiess JM (1995) Assessment of kinematic wave time of concentration. *J Hydraul Eng* 121(3):256–266
- Morgali J, Linsley RK (1965) Computer analysis of overland flow. *J Hydraul Div* 91(3):81–100
- Nguyen M, Sheath G, Smith C, Cooper A (1998) Impact of cattle treading on hill land: 2. Soil physical properties and contaminant runoff. *N Z J Agric Res* 41(2):279–290
- Penning-Rowsell EC, Tunstall SM, Tapsell S, Parker DJ (2000) The benefits of flood warnings: real but elusive, and politically significant. *Water Environ J* 14(1):7–14
- USDA SCS (US Department of Agriculture Soil Conservation Service) (1986) Urban hydrology for small watersheds, 2nd edn. Technical Release 55
- Wilby R, Greenfield B, Glenny C (1994) A coupled synoptichydrological model for climate change impact assessment. *J Hydrol* 153(1):265–290
- Wong TS, Chen C-N (1997) Time of concentration formula for sheet flow of varying flow regime. *J Hydrol Eng* 2(3):136–139
- Xu C-Y (1999) Climate change and hydrologic models: a review of existing gaps and recent research developments. *Water Resour Manag* 13(5):369–382
- Yakowitz S (1985) Markov flow models and the flood warning problem. *Water Resour Res* 21(1):81–88
- Yang X, Michel C (2000) Flood forecasting with a watershed model: a new method of parameter updating. *Hydrol Sci J* 45(4):537–546
- Younis J, Anquetin S, Thielen J (2008) The benefit of high resolution operational weather forecasts for flash flood warning. *Hydrol Earth Syst Sci Discuss* 5(1):345–377
- Yu P-S, Chen S-T (2005) Updating real-time flood forecasting using a fuzzy rule-based model/mise a Jour de Prevision de Crue en Temps Reel Grace a un Modele a Base de Regles Floues. *Hydrol Sci J* 50(2):265–278